

Study of a Narrow $\pi^+\pi^-$ Peak at about 755 MeV/ c^2 in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ Annihilation at Rest

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Abstract

A narrow peak in the $\pi^+\pi^-$ mass distribution was seen by the Rome-Syracuse Collaboration in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest in 1970. It was ignored for 40 years. The reanalysis of this peak finds that it has the mass $757.4 \pm 2.8_{\text{stat}} \pm 1.2_{\text{sys}}$ MeV/ c^2 and a width consistent with the experimental resolution. The evidence of the peak is 5.2 standard deviations. The peak is generated in $(1.03 \pm 0.21_{\text{stat}} \pm 0.21_{\text{sys}})\%$ of the $\bar{p}n$ annihilations at rest. No spin analysis is possible with the statistics of the experiment but there are arguments suggesting that it has $J^P = 0^+$.

1 Introduction

In 1970, the Rome-Syracuse Collaboration (RSC) studied the branching ratio of the decay $\omega \rightarrow \pi^+\pi^-$ [1] using the data of the $\bar{p}n$ annihilations at rest collected in the 30" BNL bubble chamber. The analysis measured the upper limit 4.3% at 95% confidence level and found an unexpected result: the $\pi^+\pi^-$ mass distribution of 1496 annihilations at rest

$$\bar{p}n \rightarrow 2\pi^+3\pi^- \quad (1)$$

had a narrow peak at about 755 MeV/ c^2 . This distribution is shown in Fig. 1a.

A χ^2 fit of this distribution found that the peak had a significance of about 4.5 standard deviations (SD) and a width lower than the experimental resolution. No relation was found between the $\pi^+\pi^-$ and other angular and mass distributions. These facts suggested to the RSC that the peak was generated by a fluctuation.

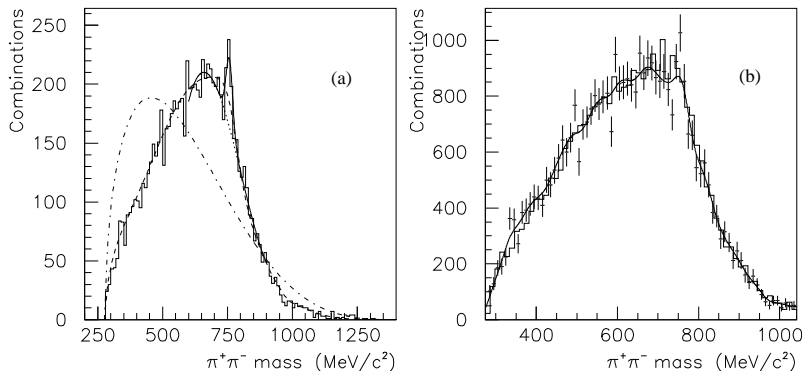


Figure 1: (a) The $\pi^+\pi^-$ mass distribution of the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilations at rest measured by the Rome-Syracuse Collaboration. The dash-dotted line is the phase space prediction; the dashed line is the prediction of the analysis of Ref. [3]; the solid line is the prediction of the fit F reported in Table I; the dotted line is the polynomial background in the same fit. (b) The $\pi^+\pi^-$ mass distribution of the $\bar{n}p \rightarrow 3\pi^+2\pi^-$ annihilations at low momenta measured by the OBELIX Collaboration; the crosses are the Rome-Syracuse data renormalized to the OBELIX combinations; the solid line is the convolution of the Rome-Syracuse data with a Gaussian having the resolution $\text{FWHM} = 37.0 \text{ MeV}/c^2$.

The properties of the annihilations (1) were understood at the beginning of 1990s [2, 3]. A reanalysis of the RSC data proved that this reaction is dominated by the channel $\bar{p}n \rightarrow f_0(1370)\pi^-$ followed by the $f_0(1370)$ decay into $\rho(770)^0\rho(770)^0$ and $S_w S_w$, where S_w indicates the $\pi^+\pi^-$ $I = 0$ S-wave interaction. The prediction of Ref. [3] are shown by the dashed curves in Fig. 1a. It fits very well the experimental data, with the exception of the interval 700-800 MeV/c^2 . The parametrization of S_w used for obtaining this curve is shown in Fig. 2.

A year after the communication of the preliminary results of this analysis [2], the OBELIX Collaboration presented the preliminary results of the analysis of the charge conjugate annihilation at low momenta [4]

$$\bar{n}p \rightarrow 3\pi^+2\pi^-. \quad (2)$$

The $\pi^+\pi^-$ mass distribution of OBELIX is shown in Fig. 1b, together with the RSC distribution normalized to the OBELIX combinations (crosses). This figure shows that the $\pi^+\pi^-$ distributions of both experiments are in agreement with the only exception of the peak at 755 MeV/c^2 that is not shown by the OBELIX data. At that time, the absence of the peak in the OBELIX data confirmed the opinion that the RSC peak was a fluctuation.

Recently, Troyan et al. claimed to have observed several narrow $\pi^+\pi^-$ peaks in the reaction $np \rightarrow np\pi^+\pi^-$ with neutrons of 5.2 GeV/c [5]. One of these

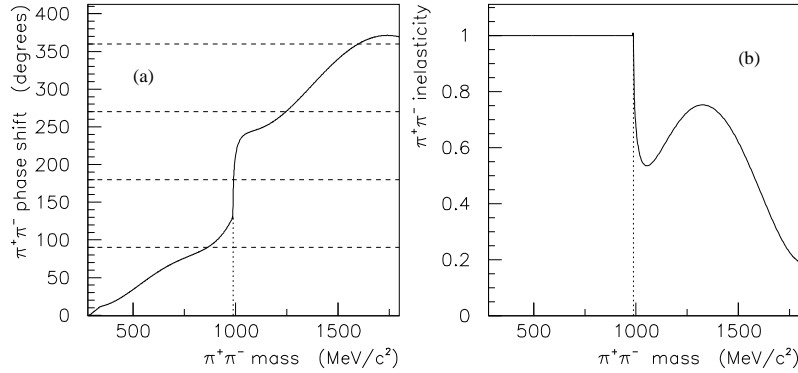


Figure 2: The parametrization RPOH4/5 of the $\pi^+\pi^-$ $I = 0$ S-wave interaction used in Ref. [3]. The dotted line shows the K^+K^- threshold. (a) Phase-shifts. (b) Inelasticities.

peak has a mass close to $755 \text{ MeV}/c^2$. The coincidence of the mass of the RSC peak with that of Troyan et al. suggested to reanalyse the RSC data.

2 Reanalysis of the Rome-Syracuse distribution

The $\pi^+\pi^-$ mas distribution of the RSC has been fitted in the mass interval $600 - 900 \text{ MeV}/c^2$ with the parametrization

$$D(m) = P_3(m) + NS(m), \quad (3)$$

where $P_3(m)$ is a third degree polinomial, $S(m)$ is the signal parametrization normalized to one, and N is the number of combinations in the peak.

The fits have been carried out either with the χ^2 or with the unbinned maximum likelihood¹ methods. Three signal parametrizations have been used:

- (a) Gaussian with the resolution σ free.
- (b) Gaussian with the resolution fixed at $\sigma = 12.74 \text{ MeV}/c^2$. (It correspond to the FWHM = $30 \text{ MeV}/c^2$ estimated by the RSC in Ref. [1].)
- (c) The double Gaussian

$$S(m) = \frac{f_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(M-m)^2}{2\sigma_1^2}} + \frac{f_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{(M-m)^2}{2\sigma_2^2}}, \quad (4)$$

¹ The maximum likelihood fits were carried out by using the known values of the $\pi^+\pi^-$ masses, which were maintained under the support of punched cards and afterwards copied manually.

Table 1: Results of the χ^2 fits of the distribution shown in Fig. 1a in the interval $600 \leq m \leq 900$ MeV/ c^2 . Fit A is the fit with σ free. Fit B is the fit with σ fixed at 12.74 MeV/ c^2 . Fit C is the fit with the resolution function (4). χ_0^2 is the χ^2 of the fit with a third degree polynomial without the signal. The last row reports the evaluation of the peak significance.

Fit	A	B	C
N (combinations)	152 ± 33	188 ± 37	220 ± 45
M (MeV/ c^2)	755.4 ± 1.9	756.3 ± 2.5	756.3 ± 2.7
σ (MeV/ c^2)	7.7 ± 1.7	12.74	
χ^2	14.7	19.6	20.5
d.o.f	24	25	25
$\chi^2/\text{d.o.f.}$	0.61	0.78	0.82
χ_0^2	44.2	44.2	44.2
$N/\Delta N$	4.6	5.1	4.9

Table 2: Results of the unbinned maximum likelihood fits in the interval $600 \leq m \leq 900$ MeV/ c^2 . Fit D is the fit with σ free. Fit E is the fit with $\sigma = 12.74$ MeV/ c^2 . Fit F is the fit with the resolution function (4). The last rows report the evaluation of the peak significance.

Fit	D	E	F
N (combinations)	147 ± 35	186 ± 36	224 ± 43
M (MeV/ c^2)	756.7 ± 1.9	757.4 ± 2.6	757.4 ± 2.8
σ (MeV/ c^2)	8.1 ± 2.1	12.74	
$N/\Delta N$	4.2	5.2	5.2

with $f_1 = 0.7483$, $f_2 = 0.2517$, $\sigma_1 = 13.24$ MeV/ c^2 , and $\sigma_2 = 32.45$ MeV/ c^2 . These number have been obtained by fitting the error distribution of the Rome subsample. (665 events.) This function has FWHM = 33.6 MeV/ c^2 .

The results of the fits with the χ^2 and with the maximum likelihood methods are reported respectively in Table I and in Table II. These fits prove that the significance of the peak is about 5 SD when the resolution is fixed using the signals (b) and (c). In particular, the fits with the maximum likelihood and the parametrizations (b) and (c) have both the significance of 5.2 SD. They prove also that the evidence of the peak was not understood in 1970s because nobody of the RSC realised that the use of the known experimental resolution would have improved the significance above five SD!

The best fit is F, because it takes into account the tails of the error distribution and is made with the maximum likelihood method. Figure 1a shows the prediction of this fit (solid lines) and of the polynomial background of the same

fit (dotted line).

3 Discussion of the difference between the Rome-Syracuse and the OBELIX data

The absence of the peak in the OBELIX $\pi^+\pi^-$ mass distributions can have two explanations: (i) the RSC peak was a fluctuation; (ii) the OBELIX Collaboration did not see the peak because the detector had a resolution poorer than our bubble chamber experiment.

The explanation (i) seems improbable because the unbinned maximum likelihood fits with the signals parametrizations (b) and (c) have the significance 5.2 SD. The explanation (ii) is possible because the OBELIX detector measured the charged pion tracks after they had traveled through the liquid hydrogen of the target and the material of the cryogenic vessel.

An indication that the OBELIX Collaboration could not have seen the peak because a poorer resolution is given by smoothing the RSC distribution. The solid line in Fig. 1b shows the convolution obtained by substituting a Gaussian having FWHM = 37.0 MeV/ c^2 to all the $\pi^+\pi^-$ masses of the RSC sample. It estimates the $\pi^+\pi^-$ mass distribution if the RSC data had had the resolution FWHM = 50 MeV/ c^2 instead of 33.6 MeV/ c^2 . (In fact, $50^2 - 33.6^2 = 37.0^2$.) This curve does not show any peak and is perfectly compatible with the OBELIX distribution.

There is a more convincing argument that supports the explanation (ii). The $\pi^+\pi^-$ mass distribution is given by

$$D(m) = \int |A(m; \{x\})|^2 d\Phi(\{x\}) = R(m)\Phi(m)$$

where $A(m; \{x\})$ is the amplitude of reaction (1) that depends on the $\pi^+\pi^-$ mass m and on a set $\{x\}$ of other kinematical variables, $d\Phi(\{x\})$ is the element of the phase space volume, $\Phi(m)$ is the phase space distribution, and $R(m)$ is the value of $|A(m; \{x\})|^2$ mediated on the variables $\{x\}$. $R(m)$ is the ratio between the experimental distribution and the phase space (REDPS)

$$R(m) = \frac{\int |A(m; \{x\})|^2 d\Phi(\{x\})}{\int d\Phi(\{x\})} = \frac{D(m)}{\Phi(m)}.$$

Figure 3a shows this ratio for the RSC data. It has two maxima: one at about 755 MeV/ c^2 , and the other at about 1250 MeV/ c^2 . The first maximum is generated by the peak under study, the second is probably due to the production of the $f_2(1270)$ meson. This ratio shows also an ankle at the $K\bar{K}$ threshold and does not show any evidence for the debated $\sigma(600)$ meson. Fig 3b shows the REDPS of the OBELIX data. It has the same behaviour shown by the REDPS of the RSC, and confirm the peaking at about 755 MeV/ c^2 . But its maximum is wider than that of the RSC and is not reproduced by the prediction of fit F.

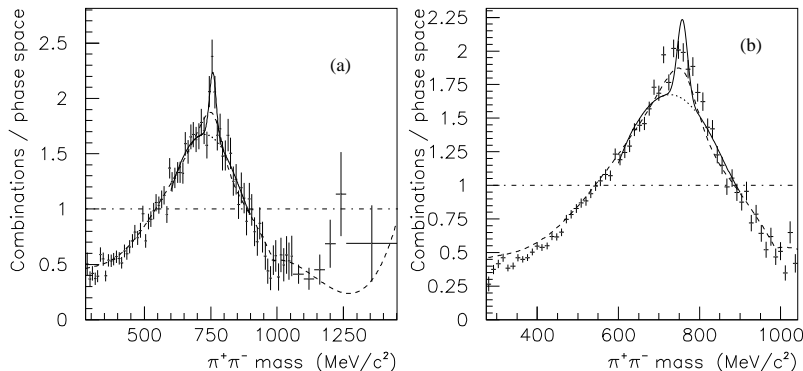


Figure 3: The ratios between the $\pi^+\pi^-$ mass distribution and the phase space predictions. (a) Ratio of the Rome-Syracuse data. (b) Ratio of the OBELIX data. In both diagrams the dashed line is the prediction of the fit made in Ref. [3], the solid line is the prediction of the unbinned maximum likelihood fit of the RSC data with the formulae (3) and (4), and the dotted line is the polynomial background estimated by the same fit.

4 Quantum numbers of the peak

The REDPS distributions prove that there is an amplitude peaking at about $755 \text{ MeV}/c^2$. This peaking cannot be generated by a reflection because no significant correlations were found between the $\pi^+\pi^-$ peak and other mass and angular distributions. The low mass suggests that it cannot have $J > 1$. Furthermore, the REDPS peak is too narrow for being produced by the $\rho(770)^0$ resonance and its mass is $25 \text{ MeV}/c^2$ far from that of the ω meson. Lastly, the peak cannot be due to the $\rho(770)^0 - \omega$ interference. In fact, the annihilations (1) are dominated by the S-wave initial states [3, 6]. Because the G-parity conservation, the channel $\bar{p}n \rightarrow \rho(770)^0\pi^+2\pi^-$ is generated by the 1S_0 state, while the channel $\bar{p}n \rightarrow \omega\pi^+2\pi^-$ is generated by the 3S_1 state. These states cannot interfere because they are not coherent.

Therefore, the best hypothesis is that the peak is generated by the $J^P = 0^+$ interaction. It could be generated by an unknown scalar meson or could be a property of the S_w interaction that was not reproduced in the previous analysis [2, 3]. In fact, the phase-shifts parametrization shown in Fig. 2a is below 90° till up $862 \text{ MeV}/c^2$. This hypothesis suggests that the peak could be reproduced by forcing the phase shift parametrization to pass at 90° at $757.4 \text{ MeV}/c^2$. Unfortunately, the events of the RSC are too low for allowing a convincing study of the effects of the variations of the $I = 0$ S-wave amplitude.

5 Conclusions

The fit F measures the following parameters for the narrow $\pi^+\pi^-$ peak shown in Fig. 1a

$$\begin{aligned} M &= 757.4 \pm 2.8_{\text{stat}} \pm 1.2_{\text{sys}} \text{ MeV}/c^2, \\ \Gamma &< 30 \text{ MeV}/c^2, \\ N &= 224 \pm 43_{\text{stat}} \pm 45_{\text{sys}} \text{ combinations}, \end{aligned} \quad (5)$$

where the systematic error has been evaluated by using the mean of the difference between the parameters found in fit F and those measured in the other five fits. The mass M is close to the values measured by Troyan et al. [5].

There is no evidence for double peak production in the same event. Therefore, one evaluates from (5) that the fraction of the channel $P(757)\pi^+2\pi^-$ in the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ is

$$\frac{N}{1496} = (15.0 \pm 2.9_{\text{stat}} \pm 3.0_{\text{sys}})\%.$$

Since the frequency of the annihilation (1) at rest is $F(\bar{p}n \rightarrow 2\pi^+3\pi^-) = (6.9 \pm 0.5)\%$ [3], the frequency of the peak is

$$F[P(757)\pi^+2\pi^-] = \frac{N}{1496} F(\bar{p}n \rightarrow 2\pi^+3\pi^-) = (1.03 \pm 0.21_{\text{stat}} \pm 0.21_{\text{sys}})\%.$$

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